Overview Of Recent Advances In Welding
- Focusing On Friction Stir Welding & Laser Hybrid Welding -

S. Marya* & **A. Gumenyuk****
* Ecole Centrale Nantes, 1 rue de la Noë, 44072 Nantes Cédex, France. E-mail : surendar.marya@ec-nantes.fr
** BAM, Federal Institute for Material Research & Testing, Berlin, Germany.

ACKNOWLEDGEMENT

This is the English translation of an article originally published in Journal of the Japan Welding Society, Vol.79, No.4, June 2010, p14-20. The Editorial Board of the Indian Welding Journal thanks the Editorial Committee of the JWS for permission to re-publish this article in the Indian Welding Journal

INTRODUCTION

The metal working sector with a turnover of about 970 billion€ represents 8% of the total EU business. Welding and joining are very important components of this industry with nearly 730,000 full time welders and 5.5 million weld related jobs in Europe[1]. It is estimated that welding generates a total added value of about 86000 million€ to the European economy. Germany, Italy and France all together make 50% of this added value as shown in Fig.1 [2]. Germany, stand first for weld equipment production worth 2550 million€, involving a work force of 15000 giving a total added value of 970 million€. Germany is followed by Italy with its 1170 million€ equipment for 6900 directly involved work force. France is third in overall production and consumable production on the European market behind Italy and Germany. Nearly 60000 trained welders and 160000 weld related jobs are involved in French economy and contribute an added value of 7800 million€ in metal working sector. The welding & joining equipment production for 2007 in France represented 320 million€, implying 1800 people and the total added value of 110 million€. However, like other developed countries, the part of manufacturing sector has undergone a severe reduction with globalization of the economy. Airbus, Ariane, TGV, Nuclear reactors are some of the vital manufacturing industrial show cases on the world stage. With enlarged European community of 27 countries with free trade and common currency in most of the member states, companies go across the borders and to examine the scope of welding in France or Germany, a larger perspective with European background needs to be kept in view.

With the emergence of low cost production facilities inherent to globalization, industry can be maintained within the European borders only if cost competitive and advanced welding methods for metal industry are developed and implemented. In the past few years, two welding technologies have advanced the scope of manufacturing by bringing quality and cost effective competiveness. Friction stir and laser hybrid technologies have overcome the technical barriers for their vast dissemination to large segments of metal manufacturing sectors. Friction stir welding invented at TWI in early nineties has contributed to the joining of otherwise non weldable or difficult to weld metals and alloys in aerospace applications. As solid state process, friction stir welds bring better joint efficiencies with reduced weld distortions. Laser hybrid welding which combines a conventional arc welding process to a high energy density laser welding reduces joint alignment & gap constraint inherent to laser welding alone. With more flexible window of joint preparation and alignment, vast applications in ship building and transport industry have explored and implemented this technology. Other sectors like oil & gas where pipe thickness is important, laser hybrid welding offers interesting perspectives though the challenges, both technical & economic, are still to be mastered [3].

In depth analysis of welding costs, even if large discrepancies exist over different sectors, suggest that nearly 70 to 75% are related to labor, 15 to 20% to materials and 1 to 2% to energy. Thus automation for reducing overall costs and energy saving by the development of more energy efficient processes in ecology sensitive world are promoted. On the same track, weight savings by the design of filler free welds is the hot topic of investigations. This is all the more important in transport sector for example in aerospace. According to rough estimates, a weight saving of a pound results in life time saving of 200USD for a civil airline, 2,000 for a military jet and a bit more than 20,000 for a rocket/launch[4]. Welding has thus to meet this trend of tailored structures with multi-materials designed to satisfy service constraints.

The objective of this short contribution is not to present an exhaustive fundamental discussion on the captioned processes, but to highlight some perspectives from authors working in two of the important European countries. What seems new or remarkable from author's perspectives is discussed here.

FRICTION STIR WELDING

Friction stir welding (FSW) invented at TWI in 1991 constituting a revolutionary concept to weld through heating and stirring [5], though it is regarded as solid state welding, which is as old as the blacksmithing. In FSW, a rotating tool-shoulder & pin or pin with non rotating shoulder-generate heat by friction and rotation and translation stir the faying surfaces to produce intermingling at atomic scale that results in sound welds generally devoid of porosity and solidification cracks inherent to fusion welding. Limited heat flow is propitious for lower distortions, residual stresses and structural gradients that make the welds not so different from parent metal. Further the absence of filler additions, a pre-requisite in case of thick welds with arc processes or laser with poor work-piece gap alignments, makes FSW an ideal process for weight saving, a vital criterion for aerospace industry. Compared to arc weld which require control over a multitude of process variables, the process parameters for FSW -rotation, translation & pressure-can be easily monitored. All mentioned weld characteristics have promoted intensive research and applications on civil aircrafts. Most of the applications are limited to high strength aluminum alloys which are prone to solidification cracking. The welding of stringers on to the fuselage of business jets and the welding of fuel tankers on space vehicles are most striking applications. However, aluminum market share on metal industry is small compared to the dominant steels- a near fourfold market. Application to steels, to some strategic aerospace materials like Titanium (14% of all materials on Airbus 380), and welding of dissimilar metals constitute the challenging assignments of researchers all over the world. Steels represent 80% of the welded products and in case of stainless steels the compliance to safety standards of hexavalent chromium emission in fusion welding is cost generator. Thus, the absence of airborne emissions in friction stir welding of stainless steels offers environmentally friendly working conditions. The absence of distortions in FSW is interesting particularly in ship building. The problem for high melting metals reside in short tool life coupled with high tooling priced materials with special treatments. Tool materials include polycrystalline cubic boron nitride (PCBN) and newly developed composite tool fabricated from PCBN and W-25Re[6]. Amongst different tracks, friction stir coupled with preheating with laser are investigated for welding of high melting temperature metals or for dissimilar joints such as copper to aluminum or aluminum to steels. The latter has a niche of applications in automotive industry which is confronted with gas consumption mileage, carbon emission and looks for weight saving applications. The friction stir spot welding between aluminum alloys and of dissimilar joints such Al-steel is a subject of great interest to academics and automotive industry. FSSW is a cost competitive solution compared to resistance spot welds in automotive sector as it is more energy efficient, less fume generator and less sensitive to surface preparation of overlapping surfaces. Whatever the friction process, friction stir or friction stir spot (FSSW), some of the fundamental and related problems of friction stir welding that draw large spectrum of investigations are as follows:

- Material flow in stir welding
- Tooling material & tool geometry
- Gap tolerance and fixtures
- Machine kinematics and robotic applications
- Modeling of friction stir process
- Metallurgical & mechanical characterization
- Non destructive testing
- Repair procedure and consequences

Besides application for metals industry, a recent promising application is the joining of wood. In Europe and all over the world, joining of wood is accomplished with adhesives and glues which are not environmentally friendly. In France alone, it is estimated that about 100,000 tones per year of furniture adhesives of petrochemical origin are used. The application and work developed by a French-Swiss team eliminates the need of adhesives was awarded 2005 Schweighofer prize for their work on wood welding (Fig.2). By the application of friction -linear friction or other variants- at temperatures above 180°c, the characteristics of lignin and hemicelluloses between the cell walls of the wood change and they start to flow. Subsequently such released wood fibers become entangled and result in welding on cooling [7]. Thus the process is very fast some seconds-compared to glues that require much longer setting times. Research work is still in progress and applications in sport goods are anticipated.

Linear friction welding of titanium for the manufacturing & repair of bladed disks (BLISKS) and rings (BLINGS) is another frictional process of great interest. For aero engine applications, a weight reduction in order to increase thrust to weight ratio is a challenging assignment for coming years. Europe has a very important aeronautic sector with Airbus, BAE, Safran group, Rolls Royce group, Dassault aviation etc. The blades are mechanically fitted through nuts and bolts in slotted zones of the forged disk. Weight savings of the order of 30 to 60% are feasible by replacing nuts & bolts by welding or by machining from blocks of metal. The machining is complex, slow and expensive route to the manufacturing of the monolithic part, compared to linear friction welding. The LFW is a 4 phase process starting from 1) reciprocating linearly of the parts under pressure which smoothens the surface asperities, 2) formation of a soft plasticized interface layer, 3) expulsion of the soft layer under axial pressure and shortening of the workpiece and finally 4) stopping of the relative motion in predefined position and application of sudden forging pressure to ensure complete welding. This process can be assimilated to the flash welding that has been used for many years to manufacture reactor rings in titanium, except that frictional heat replaces high currents in flash welding. For the manufacturing of blisks using LFW, main problem lays with the machine itself to enable the chain of operations to weld individual blades on curved surfaces while maintaining precise compliance to defined part profiles (Fig.3). Currently, chordal type (LFC) and tangential type machines (LFT) are thought of for blisk manufacturing. Chordal type machines are the simplest as only two axis-forging & moving axes are needed. In tangential type machines, due to high tangential forces on the disk, a much stronger clamping is required [8]. Recently a company has started manufacturing LFW machines which are characterized by two axes of pressure to generate complex joints such as T joints or welding & forming of complex parts with stingers [9]. Though fusion welding (laser or electron beam- might do the welding job, the main risk is the presence of defects such as undercuts, cracks and porosity that would render the weld inapt for secure applications. Further fusion welding would very likely introduce important distortions to parts where part profile is prime importance. Investigations on LFW of titanium and nickel base alloys must be undertaken developing theoretical models of heat generation, material softening, deformation and ejection during the forging phase, welded structures in the weld and heat affected zones, effect of parameter sequencing (amplitude & frequency of relative movement, axial pressure, forging pressure) on part reduction or material consumption and geometrical precision of welded parts. Further more detailed work both on machine design and parameter optimization is required to implement aeroengine applications.

LASER WELDING &HYBRID LASER ARC WELDING

Lasers ever since their invention in the early seventies have gone from tales of science fiction to operational tools for manufacturing to life support applications. Practically for each application, a laser wave length, power and beam delivery mode is now available. In the early phases of their acceptance in welding related sectors, it was the ease of welding in air with narrow beads and heat affected zones, and concomitant low distortions coupled high productivity that attracted attention. Increasing power levels, widening of wavelength spectrum from ultraviolet to infrared and cost reduction of laser sources gave further impetus to their integration in manufacturing. CO_2 lasers with power levels of 45kW are now in industrial applications, Nd:YAG laser have seen improvements in their beam quality and the introduction of fiber and disk lasers with power levels approaching 30 kW range with low BPP with high efficiency of 30% and more allow new fields of applications. The steady increase in available power as shown in Fig.4 [10] sets no limit and from welding perspectives, it seems that the maximum level has already been achieved for major industrial applications. Following their aforementioned characteristics, fiber lasers now occupy a large segment of world laser market and account for 9% of laser metal applications, behind the CO_2 (68%) and solid state lasers (23%) [11].

Much fundamental understanding of laser material interactions has given confidence in the stability and repeatability of results. One of the earliest problems facing laser integration in manufacturing of large consumer market products- automotive sector for instance- was what constituted their strong point, small focusing capacity. Small focused spots implied narrow gaps and best part alignments. This required cost generating machining of parts and design of complex fixtures. It was estimated that gaps of the size of the beam focus would never be correctly welded and as small spots were required for high power densities, a compromising solution was and is always delicate. Though dual focus through beam splitting, or weaving of the beam seemed to offer some alternatives to gap constraints, a filler material was required to fill the gap & also to reduce solidification cracking of welds. Filler melting under the laser introduced more constraints on overall performance and it soon became evident that filler melting would be more economic with electric arc than laser beam itself. This combination gave birth to laser arc hybrid welding that has opened new venues of applications, for instance in ship building and pipe line industry. Though, the hybrid laser arc welding technology may involve TIG, GMAW or plasma arc as shown in Fig.5, it's mainly the combination with GMAW that has become the main focus of applications. The general synergic contribution of GMAW and laser in hybrid laser arc welding is outlined in Fig.6

In automotive sector where consumers demand low carbon emission and high fuel efficiency, weight reduction is a major challenge. It's a common belief that with reference to 2000 year cars, ULSAB-AVC would use nearly 85% of UHSS or AHSS (ultra or Advanced high strength steels) and laser brazing and welding would constitute more than 70% of the projected joining applications. For more advanced steels, high strength is usually obtained through carbon & alloying additions. The perspective of developing martensitic phase in the weld metal then becomes a major concern from formability view point (Tailored blanks). Higher welding energy from laser, reduction in the welding speed and the use a filler to modify chemical composition of weld bead constitute some of the tracks to overcome this concern. Reduction in welding speeds is incompatible with high production rate common in automotive sector. The other possibility is to add an arc process (TIG or GMAW) to increase weld energy at a low cost that would further bridge the gaps between parts. However, it might still be difficult to reduce HAZ hardness in case of UHSS steel with laser arc hybrid process alone [12]

New applications demand extensive feasibility studies before acceptance. For instance, laser arc hybrid technology is now widely accepted in ship building (Mayer Werft, Blohm & Voss, Acker Yards, Fincantieri..) underwent a long cycle of development from lasers to laser arc hybrid. This necessitated a concerted effort of ship building industry, academics and European projects to develop the process itself, evaluate the mechanical, metallurgical and service characteristics of joints, examine safety requirements and validate repair procedures along with NDT results to get acceptance from different authorization bodies. Hundred percent NDT examinations of welds to exclude any risk of solidification cracks became restraining for lasers. The advent of laser arc hybrid which reduced and eliminated solidification crack occurrence and enlarged the window of part alignment, the process level confidence increased and paved way to new applications that are now becoming common. Prior to laser arc hybrid welding, ship building relied on submerged arc and MIG/MAG processes for relatively thick parts common in ships. However, these processes are not only relatively slow but also introduce high heat input to the weld that generates distortions (Fig.7). As ship building is mostly an assembling process, sub assembly distortions require time consuming corrective operations before final assembling. Laser arc hybrid processes introduce less heat, much smaller distortions and are more cost effective & productive than the arc processes.

Notwithstanding the recent availability of high power lasers, their effective application for welding of thick sections are sometimes limited by physical and metallurgical phenomena. The scaling of the weldable material thickness over 10 mm remains problematic by simple increasing of the output power of the laser due to complex laser material interactions. Some of the problems limiting the range of application of lasers to the welding of thick materials are following:

- gap tolerances decreasing with increasing thickness of welded material
- evaporation phenomena strongly

influencing the stability of the process

- restricted transport of the filler material into the depth of the melt pool
- increasing risk of appearance of solidification flaws with increasing plate thickness

More than often, the shift from laser to laser hybrid welding helps to solve some of these problems. It has been demonstrated that hybrid process is less sensible to instabilities of the keyhole compared to pure laser welding. The gap tolerances can be increased significantly compared to lasers with or without filler, gap and part alignment tolerances are also less severe and weld metal chemistry is better controlled to eliminate solidification cracking problems [13]

One sector of vital importance to world energy supply and transport is the line pipe strings that are girth welded by manual or semi automatic arc processes (Stick electrodes, MIG/MAG, flux cored wire, Tandem arc welding). Arc welding processes are slow and for large diameter pipes of 1.22 m (48") with wall thickness range to 35 mm and plus, welding becomes a major problem in progression of pipe line. Rough estimates yield pipe welding costs as 25% of the total project cost, besides the fact that welding is often at the root of delays in project execution. Further skilled welders are becoming scarce and work conditions in harsh to severe field conditions are not attractive to urban workers. Further, oil & gas industry is looking for high strength materials to reduce wall thickness of pipes or to gain in the allowable pressure for a greater transport of gas. The industry is shifting from 500MPa steels or X65 to higher grades X100 and projecting to increase internal pressure from 1000-1500psi to 2000-2500 psi range. From metallurgical view point, weldability of steels becomes more difficult with increasing strength and a better joint efficiency management requires a strict control over the weld parameters. A fully automatic welding would be the best approach to dissipate concerns on weld quality variability. Amongst other competitors (Arc welding, flash butt welding, rotating arc..), high energy density processes (electron beam, lasers) are becoming more attractive. Electron beam welding which is efficient in vacuum seems to present higher technical complexities and probably not well adapted to line pipe applications involving thick walled pipe. Lasers on the other hand can be operated in air and offer better perspectives. Thus, it's a general thought that fully automatic laser arc hybrid welding would generate significant cost benefits. Because of gravity effects in out of position welding it is still questionable if single pass butt welding of thicknesses beyond ca 15mm in all positions will ever be possible, even if laser powers will be ever increasing. From this point of view laser powers of 15 to 20 kW might be potential candidates for orbital welding, where beveled joints would be required.

The idea to use laser for welding of pipelines is not a new one. Several research works have been published since 2000 where the authors proposed to use CO_2 [14] or Nd:YAG lasers[15] to integrate laser based welding technology for orbital pipeline welding. The weld thickness was mostly restricted to the value of 10 mm by producing either a single run or a root run for multi-run welding of line pipes of C-Mn steels. One but not the only reason for such kind of restriction was the power of the available laser systems of 12 kW CO_2 or 4.4 kW Nd:YAG. As line pipe welding is field operation with heavy wall thickness, a high power, compact and energy efficient laser becomes a sine quoi non condition. It's only recently that high power lasers (fiber & disks) with energy efficiency of 30%, power levels of 30kW and still on the rise, with high beam quality and transfer with fibers, have been marketed. This meets the first requirement of line pipe industry and opens the route to girth welding using laser arc hybrid technology. New possibilities are now open to establish a welding process for up to 20 mm thick welds and even thicker for single-run welding [16] as recently reported by Rethmeier et al. This new weld design can result in a significant reduction of welding consumables. The higher welding speed of the laser beam welding process compared to conventional welding would result in a reduction of the production cycle time and in the long run in a reduction of the number of welding stations working/operating in pipeline construction at similar productivity as a conventional system. This direct comparison hence shows that by application of laser-hybrid welding for a 20 mm thick pipe the consumption of consumables can be reduced by the factor of 5 compared to gas metal arc (GMA)-tandem welding which is considered to be the most productive welding technology for pipelines, and even by the factor of 10 compared to manual metal arc welding (MMAW) which constitutes a greatest part of all welding technologies applied nowadays in pipeline construction. The difference is still more pronounced when a single weld production time is compared. Thus, for example, producing a complete weld will take about 1.5 min in case of laser hybrid welding, about 12 min in case of GMA-tandem welding and about 190 min in case of manual metal arc welding. At the same time, the energy consumption, despite of still relatively low energetic plug efficiency of modern solid state lasers (approximately 30%) is comparable to that of GMA-tandem welding and an order of magnitude lower than that of manual metal arc welding. This is the reason why laser-hybrid welding can be considered as a sustainable method of production preserving resources and contributing to public health protection. Fig.8 shows orbital welding equipment that has undergone and is used in investigations on orbital welding of large diameter pipes at BAM. Preliminary studies on gaps and alignments have shown that with a scanning system, gaps of the order of 0, 7mm might be acceptable (Fig.9). As far as misalignments along radial axis of pipes, 2mm max seems to be the limiting value. The window of acceptable preparations and alignments are some of the pre-requisites to the development and implementation of industrial machines. This would involve internal & external clamping systems of pipes in field environment (Fig.10). Further, field tests with proven results on weld quality with the cost competitiveness to existing technologies would be required before any wider acceptance of laser arc hybrid technology to the orbital welding of line pipes.

CONCLUSIONS

The short overview of welding with more detailed focus on Friction stir welding and Laser hybrid welding presented here outlines some historic perspectives and gives future trends. In a competitive technology market, where more than thirty known processes for welding assignments are available, the choice of the welding process is determined by national cultures and the industrial base. In Europe where aviation, transport and ship building are the principal vectors of economic development, the sustained growth can only be assured through innovation. Welding processes mentioned here offer cost effective competitive manufacturing routes. Still more fundamental work coupled with optimized design and marketing of fully automatic machines is needed for challenging applications such as blisks and line pipe welding.

REFERENCES

[1] S.Escala, M. Nooij, L.Quintino: Economically welding in healthy way, European Welding federation doc 5, 2006 www.ewf.be

[2] Newsletter EWF/IAB N°26

[3] Hybrid Laser-arc Welding, Ed F.O.Olsen, Woodhead publishing Ltd.

[4] P.F Mendez & T.W.Eager: New trends in welding in aeronautic industry, in 2nd Conf on trends in aeronautic industry, Bilbao, Spain, Nov 19-20(2002)

[5] W.M. Thomas, E.D. Nicholas, J.C. Needham, M.G. Murch, P. Temple-Smith, C.J. Dawes: Friction Stir Welding, International Patent Appl. N° PCT/GB92/02203, (1991).

[6] M. Mahoney, T.Neslson, C. Sorenson: Friction stir welding of ferrous Alloys Current Status, Material Science Forum Vols 638-642, pp 41-46 (2010)

[7] Citation from SNS news 4, 2005

[8] A. Petiot: Linear friction welding and aerospace applications, Journées Technologique Titane, Assocation Ti, Nantes, May 2008.

[9] www.acb-ps.com/fr

[10] F.Vollertsen, S. Grünenwald: Thick section welding on right track to industrial applications, Proc., Int. Colloquium High Power Lasers, Oct 12-13, BBAM, Berlin

[11] David A. Belforte :Economic review and forecast, Industrial Laser Solutions, pp 5-10, January/February (2009)

[12] F.Briand, O.Dubet, P.Lefebvre, G.Ballerini: Laser and hybrid welding of high strength steels, Competences, Technical Jl. of Oerlinken Co., pp26-33, May 2009

[13] J.K.Kristensen: Shipbuilding applications of hybrid laser arc welding, Chapter 8 in Laser Hybrid welding Ed by F.O.Olsen

[14] Y. Gainand et al.: Laser orbital welding applied to offshore pipe line construction. Pipeline technology Vol. II Elsevier Science, pp. 327-343, (2000)

[15] S. Fujinaga, et al.: Development of an all-position YAG laser butt welding process with addition of filler wire, Welding Journal, 19, pp. 441-446, (2005)

[16] M. Rethmeier et al.: Laser-Hybrid Welding of Thick Plates up to 32 mm Using a 20 kW Fiber Laser. Proceedings of the 8th International Welding Symposium, Innovations in Welding and Joining for a New Era in Manufacturing. Japan Welding Society. LW-11, p. 43, (2008)

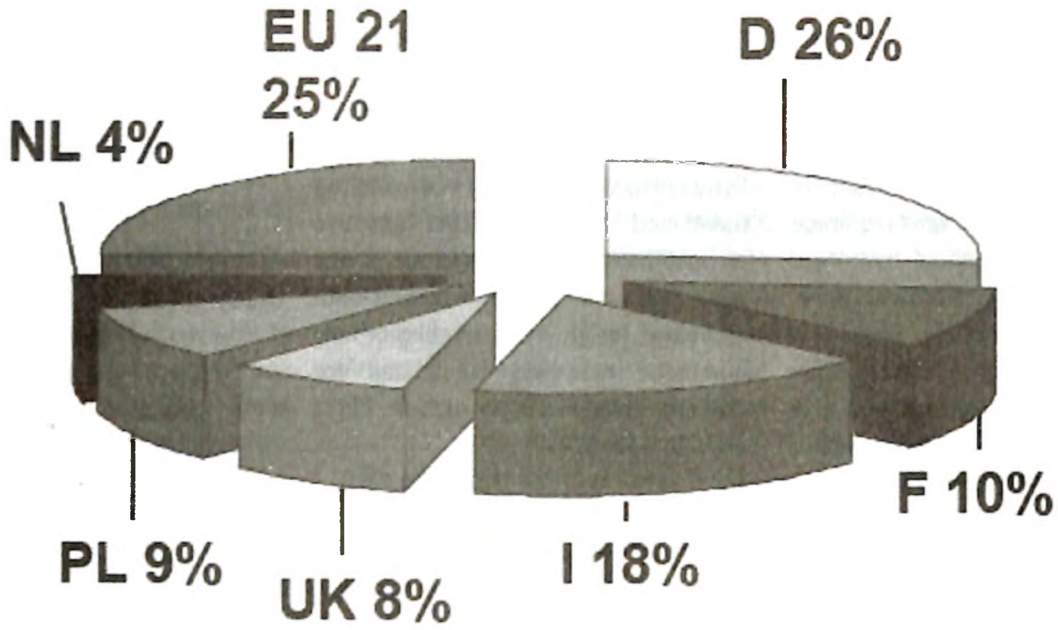


Figure1 : Added value from welding in EU 27 countries [2]

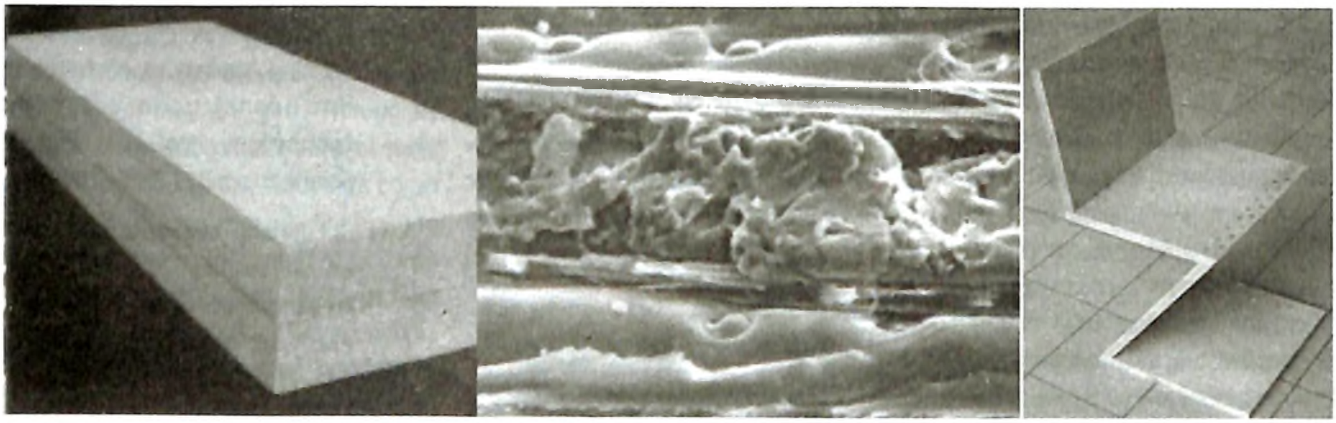


Figure.2 : Welding of wood (left) SEM image of the fractured joint (middle) and minimalist Rietfeld chair done exclusively by dowel welding [3]

Figure 3 : Schematic view of BLISK manufacture, from left to right- forged disk, machined disk, blade et linear friction welding to a final disk. The flash left by LFW is machined [8].

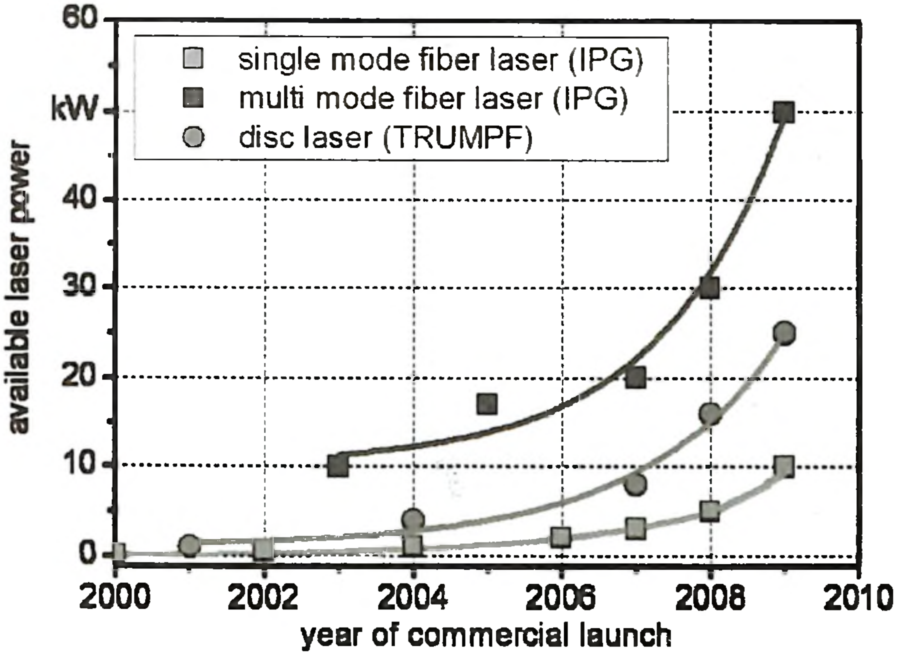


Fig.4 Progression of laser power from fiber and disk lasers [10]

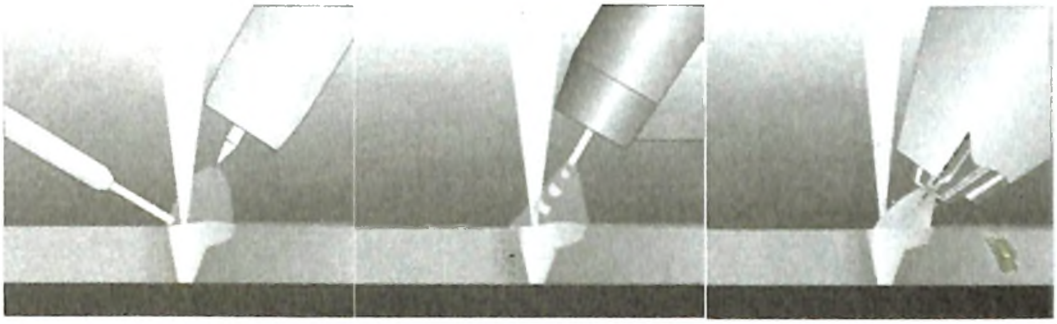


Fig.5 Different laser arc hybrid processes (left) with TIG, with GMAW (middle) and plasma (right)

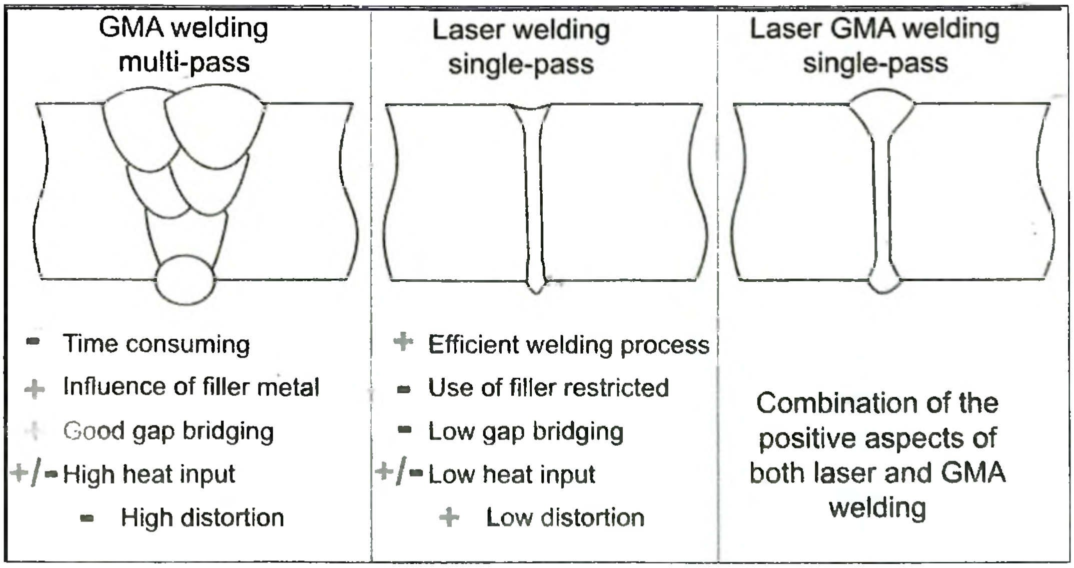


Fig.6 Synergic benefits from Laser GMAW hybrid welding process

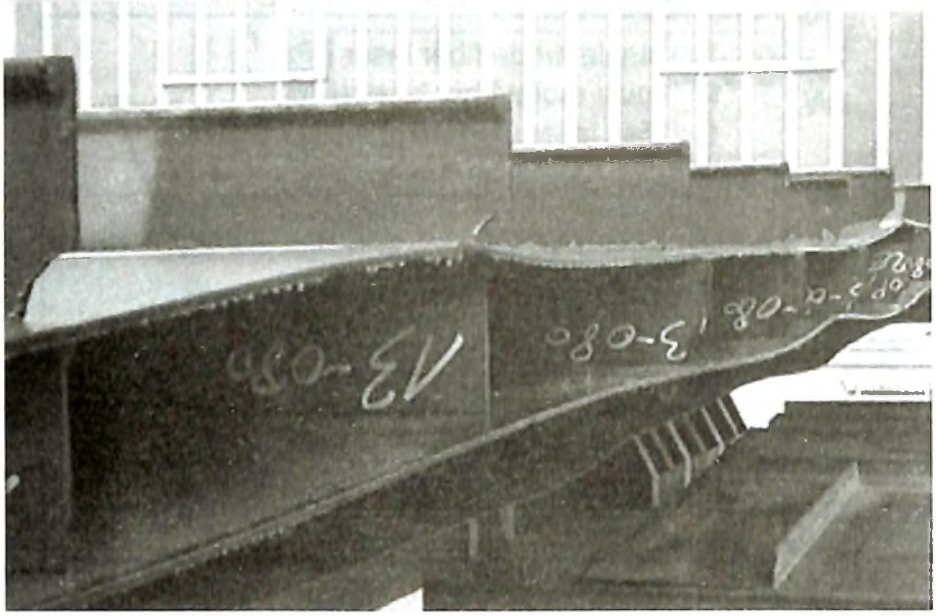


Fig.7: Arc welded deck panels distortion control as the most motivated factor for laser arc hybrid welding (doc J.K. Kristensen, Force Technology)

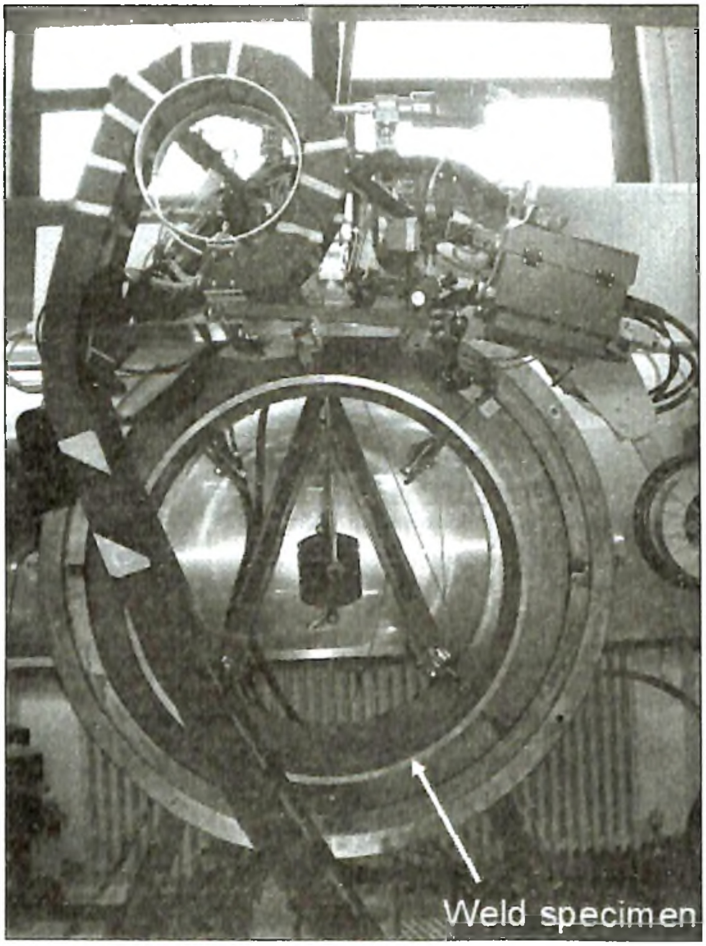
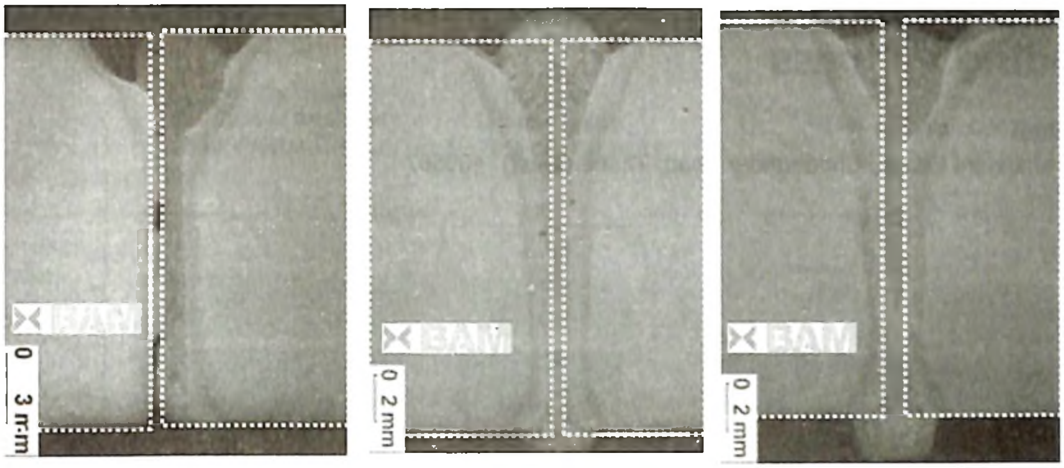


Fig.8: Orbital welding equipment with laser arc hybrid weld head for large diameter pipes at BAM



Gap 0,5 mm **Gap 0,5 mm** **Gap 0,7 mm**

Fig. 9: 0,5mm gap (left) without scanning compared to 0,5mm gap (middle) and 0,7mm gap (right) both with scan width of 0,7mm at 200Hz, 16mm thick plates

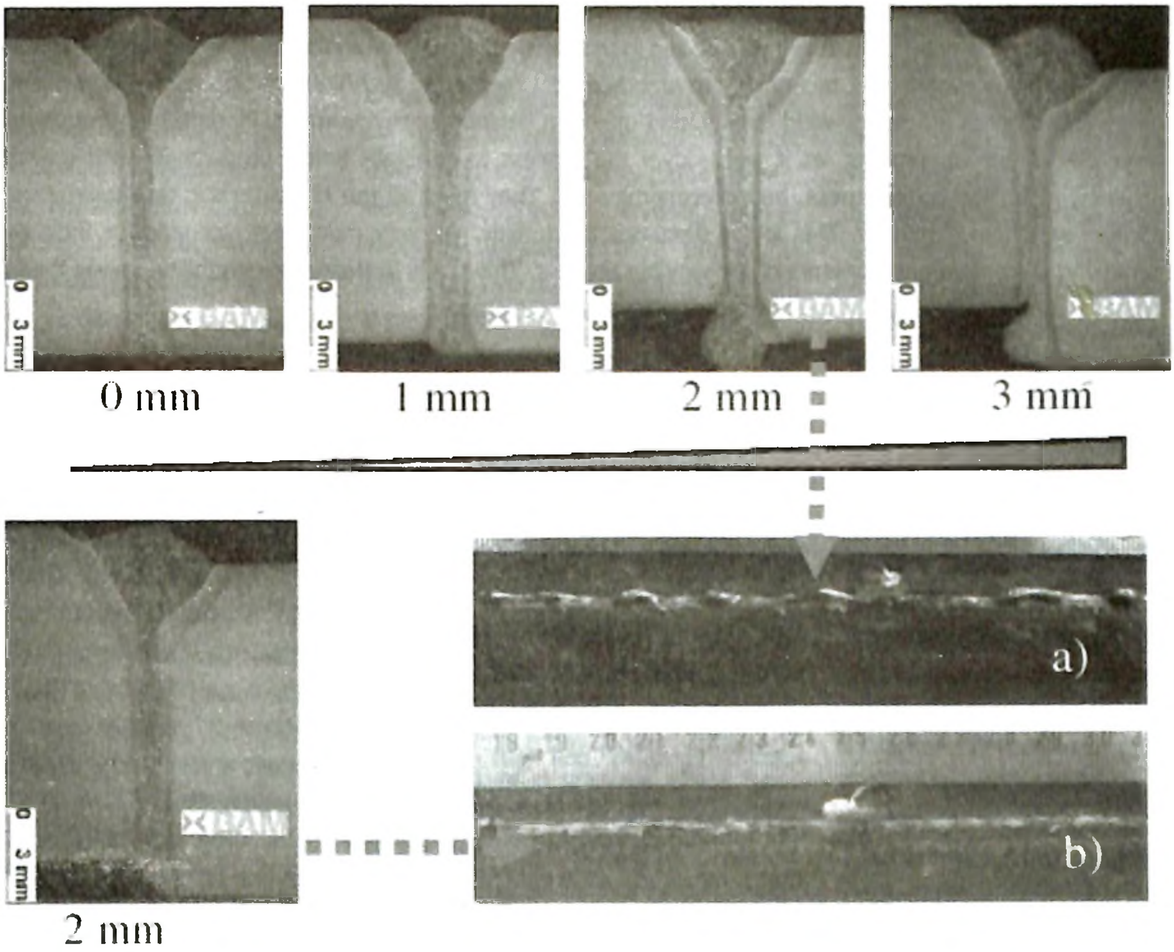


Fig. 10 : 16 mm weld cross-section with varying edge misalignment (the root side pictures correspond to 2 mm edge misalignment welded without a) and with b) parameter variation).